DEVELOPMENT OF NEW GENERATION OF MULTIBODY SYSTEM COMPUTER CODES

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Multibody system (MBS) computer codes currently being used are based on three-decade old technology that is failing to respond to new modeling challenges. Modern and complex ground vehicle models, for example, include significant details that cannot be captured using existing MBS software technology. This paper discusses a new Department of Defense (DoD) initiative focused on the development of new generation of MBS computer codes that have capabilities and features that are not provided by existing MBS software technology. This old technology fails to meet new challenges of developing more detailed models in which the effects of significant changes in geometry and large deformations cannot be ignored. New applications require accurate continuum mechanics based vehicle/soil interaction models, belt and chain drive models, efficient and accurate continuum based tire models, cable models used in rescue missions, models that accurately capture large deformations due to thermal and excessive loads, more accurate bio-mechanics models for ligaments, muscles, and soft tissues (LMST), etc. Addressing these modeling and virtual prototyping challenges is necessary in order for industries and federal laboratories to have a new generation of MBS software that will serve their mission. The development of such a new software technology will require a successful integration of computational geometry (CG), FE, and MBS algorithms. Existing MBS algorithms have a structure and formulations that do not allow for such a successful CG/FE/MBS integration. The kinematic description used in existing finite element formulations is not consistent with CG methods (B-spline and NURBS) used in CAD, that is, the geometry of CAD models is not preserved when these models are converted to a FE mesh for performing the analysis. Furthermore, the use of CG methods as analysis tools is also not recommended for MBS applications that require certain treatments of the joints and constraints. For this reason, a fundamentally different FE approach is required for the new integration of CG, large displacement FE, and MBS algorithm. This will be accomplished in the DoD initiative using the nonlinear FE *absolute nodal coordinate formulation* (ANCF) that has many desirable features. This paper discusses the feasibility of developing such a new software technology that is required for accurate virtual prototyping of vehicles, machines, and equipment.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
02 NOV 2012	**Journal Article**	**10-07-2012 to 22-10-2012**

4. TITLE AND SUBTITLE
DEVELOPMENT OF NEW GENERATION OF MULTIBODY SYSTEM COMPUTER CODES

5a. CONTRACT NUMBER
W56HZV-13-C-0032

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ahmed Shabana; Paramsothy Jayakumar; Michael Letherwood

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Mechanical and Industrial Engineering,University of Illinois at Chicago,842 West Taylor Street,Chicago,IL,60607

8. PERFORMING ORGANIZATION REPORT NUMBER
; #23457

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
#23457

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This paper discusses a new DoD initiative for the development of a new generation of MBS software technology that will allow for the integration of computer aided design and analysis (I-CAD-A). The new computational environment will be used in the simulation of models that include details that cannot be captured by existing MBS software.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**14**	

1. BACKGROUND

Multibody system (MBS) computer codes are used in the design, virtual prototyping, and performance evaluation of industrial and technological systems including ground vehicles that operate in hostile environments. These computer codes are designed to automatically construct and numerically solve the differential and algebraic equations that govern the motion of systems that consist of interconnected rigid and deformable bodies. While such computer codes are widely used as the basis for the design of automotive, aerospace, robotics, and machine systems as well as in modeling bio-mechanics and biological systems among many others, these codes are based on three-decade old technology that is failing to respond to new modeling challenges. Modern and complex ground vehicle models, for example, include significant details that cannot be captured using existing MBS software technology. For this reason, the Department of Defense (DoD) launched a new initiative for the development of a new generation of MBS computer codes that have capabilities and features that are not provided by existing MBS software technology.

MBS-simulation programs used in the analysis of models that consist of rigid components were introduced in the mid seventies. The integration of *small deformation* finite element (FE) and MBS algorithms was successfully accomplished approximately three decades ago (early eighties). This old technology, which has been used extensively and has served well the industry, federal laboratories, and academic research, has capabilities and features that will remain as important options for modeling small deformations in MBS system applications. Nonetheless, this old software technology cannot be used to meet the new challenges of developing more detailed models in which the effects of significant changes in geometry and large deformations cannot be ignored. New applications require accurate continuum mechanics based vehicle/soil interaction models, belt and chain drive models, efficient and accurate continuum based tire models, cable models used in rescue missions, models that accurately capture large deformations due to thermal and excessive loads, more accurate bio-mechanics models for ligaments, muscles, and soft tissues (LMST), etc.

Addressing these modeling and virtual prototyping challenges for systems as the one shown in Fig. 1 is necessary in order for industries and federal laboratories to have a new generation of MBS software that will serve their mission. The development of such a new software technology will require a successful integration of computational geometry (CG), FE, and MBS algorithms. Existing MBS algorithms have a structure and are based on procedures and formulations that do not allow for such a successful CG/FE/MBS integration. The kinematic description used in existing finite element formulations is not consistent with CG methods (B-spline and NURBS) used in CAD, that is, the geometry of CAD models is not preserved when these models are converted to a FE mesh for performing the analysis. The use of CG methods as analysis tools is also not recommended for MBS applications that require certain treatments of the joints and constraints (Hamed et al., 2011; Shabana et al., 2012). For this reason, a fundamentally different FE approach is required for the new integration of CG, large displacement FE, and MBS algorithm. This can be successfully accomplished in the DoD initiative using the nonlinear FE *absolute nodal coordinate formulation* (ANCF) that has many desirable features (Dufva et al, 2005; Garcia-Vallejo et al, 2008; Schwab and Meijaard, 2010; Shabana, 2012; Tian et al, 2009). These ANCF features will allow for developing an efficient interface between CAD systems and MBS software using linear transformations, and will also allow for developing more general material models and for systematically capturing the effect of large deformations (Shabana, 2012).

Figure 1. Vehicle systems

It is the objective of the DoD initiative to develop a new software technology that will lead to a new computer code that

1. is fundamentally different in structure from existing MBS codes,
2. requires the development of new and innovative algorithms that exploit the sparse matrix structure of the MBS equations of motion developed using new large displacement finite elements,
3. ensures that MBS kinematic and joint constraint equations are satisfied at the position, velocity, and acceleration levels when implicit and explicit numerical integration methods are used,
4. allows for accurate and efficient modeling of large deformation in MBS applications,
5. allows for developing new joint formulations that are based on linear connectivity conditions leading to FE meshes that have constant mass matrix and zero Coriolis and centrifugal forces,
6. allows for the use of general continuum mechanics approach and material models, and captures the effects of thermal loading, excessive forces, and soil deformations; and
7. captures modes of deformations that cannot be captured using existing FE/MBS algorithms.

This paper discusses the feasibility of developing such new software that will represent a new generation of MBS computer codes capable of capturing details that cannot be captured using existing MBS software technology. In order to ensure the success of this DoD initiative, preliminary studies have been already conducted to demonstrate some of the new capabilities that will distinguish the new software technology. These preliminary studies are documented in several articles (Contreras, et al, 2011; Hamed et al., 2011; Lan and Shabana, 2010; Sanborn and Shabana, 2009; Shabana and Hussein, 2009; Shabana et al., 2012).

2. SCOPE OF THE INVESTIGATION

The three-decade old MBS software technology has serious limitations when used in the analysis, design, virtual prototyping, and performance evaluation of modern vehicle systems. These limitations are well known and are documented in the literature (Shabana et al, 2007). The analysis of modern vehicle systems requires the development of complex models that include details that cannot be captured or accurately simulated using existing MBS codes which are based on rigid body assumptions or small deformation FE formulations that are not suited for efficient communications with CAD systems. It is, therefore, necessary to develop a new MBS software technology that is based on new concepts and algorithms that can be used for accurate and efficient simulation of wheeled and tracked vehicle models that include significant details. A successful integration of computational geometry (CG) methods used in CAD systems, nonlinear large displacement finite elements (FE), and flexible multibody systems (MBS) algorithms is necessary for the development of these new algorithms. In this section, some of the fundamental issues that need to be considered in the development of the new technology are discussed.

2.1 Integration of CG/FE/MBS Algorithms

The successful integration of CG, FE, and MBS algorithms can be accomplished using the absolute nodal coordinate formulation (ANCF) which has many desirable features that can be exploited in developing

new MBS software technology. CG B-spline and NURBS representations can be converted without any distortion to an ANCF mesh. This unique feature allows for developing a simple interface based on linear transformation between the B-spline control points (shown in Fig. 2) and ANCF nodal coordinates. This ANCF feature is unique since it is not shared by other FE formulations. Existing FE formulations do not lead to a geometry that can be converted exactly to CAD geometry as discussed in the literature (Hamed et al., 2011; Shabana et al., 2012). This geometry distortion that makes analysis models different from the original CAD models and costs the U.S. Automotive Industry alone more than $600 m/year (Mackenzie, 2011) can be avoided using ANCF finite elements; thereby allowing for developing FE meshes that have identical geometry to the geometry developed in CAD systems. Having an efficient interface between CAD and analysis is necessary when vehicle components of complex geometry are considered. ANCF finite elements also allow for a more general geometric description than B-spline and NURBS which employ rigid recurrence formulas and the concept of the knot multiplicity. ANCF finite elements also allow for modeling structural discontinuities that cannot be modeled using B-spline and NURBS geometry (Shabana et al, 2012). For this reason, ANCF finite elements are suited to the integration of computer aided design and analysis (I-CAD-A).

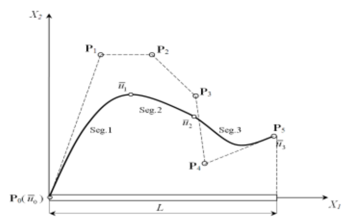

Figure 2. Control points

2.2 Large Deformations and Material Models

Existing commercial flexible MBS computer codes are based on the floating frame of reference (FFR) formulation which employs linear modes for the description of the body deformations. Consequently, the FFR formulation is suited, for the most part, for the analysis of small deformation problems only. Large deformation problems cannot be systematically solved using the FE/FFR formulation implemented in most commercial MBS codes. Furthermore, existing structural finite elements such as beams, plates, and shells implemented in both commercial FE and MBS codes are based on simplified elasticity approaches and/or classical beam and plate theories. These widely used structural finite elements do not allow for the use of a general continuum mechanics approach or the use of general material models. Use of more general constitutive models, such as Neo-Hookean, Mooney-Rivlin, and soil constitutive laws, requires a more general kinematic description than the one used in these conventional elements (Ogden, 1984; Shabana, 2012). ANCF finite elements, on the other hand, do not suffer from this serious limitation since these elements have a kinematic description that is consistent with the general theory of continuum mechanics. Because ANCF finite elements employ absolute position and gradient variables as nodal coordinates, they correctly describe arbitrary rigid body displacements including general three-dimensional rotations. For this reason, ANCF finite elements allow for the use of general material models such as Neo-Hookean, Mooney-Rivilin, and soil constitutive laws. This unique feature of ANCF structural elements (beams, plates, and shells) allows for developing accurate FE models for tires, belts, rubber chains, cables, etc. Another important issue related to the generality of the dynamic models is the displacement modes captured by the solution algorithms. The structural finite elements (beams, plates, and shells) used in existing MBS and FE commercial codes assume that the cross section remain rigid and/or the thickness of the element remains constant. Because of this assumption, deformation modes such as stretch or change in the dimension of the element cross section due to thermal loads and/or excessive tensile or compressive forces are not captured when these structural finite elements are used. A new generation of MBS computer codes that do not suffer from these limitations can be developed based

on the ANCF finite element description. These codes will allow for the use of a general continuum mechanics approach, the use of general constitutive equations, and the capturing of significant deformation modes that cannot be captured using existing FE and MBS codes. Figure 3 shows numerical results of a beam that is subjected to an axial force (Maqueda and Shabana, 2007). The beam is modeled using ANCF fully parameterized beam elements that capture the deformation of the cross section. The cross section deformation measured by Nanson's formula that gives the ratio between the area in the deformed and undeformed configuration is shown in the figure when different general material constitutive models are used. The results presented in this figure shows that the linear Hookean material model leads to zero cross section dimension, while the nonlinear models correctly capture the cross section deformations and do not lead to zero cross section. Existing structural FE formulations cannot capture this change because such formulations assume that the cross section of a beam, for example, remains rigid.

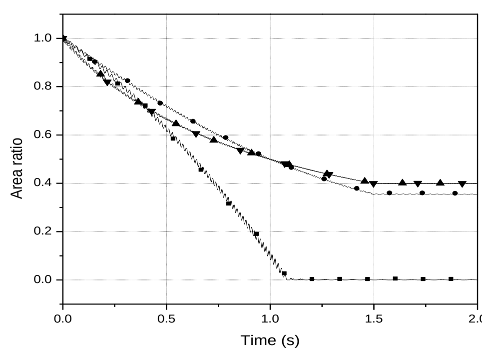

Figure 3. Area ratio at the center of the beam using two elements, and linear and nonlinear constitutive models for the tensile test (—■—, Hookean; —●—. Compressible Neo-Hookean; —▲—, Incompressible Neo-Hookean —▼— Mooney-Rivlin).

2.3 New Kinematic and Inertia Description

Another serious limitation of the algorithms used in existing commercial MBS codes becomes clear when tracked vehicle models, as the one shown in Fig.1, are considered. These algorithms lead to highly nonlinear joint formulations and a highly nonlinear generalized inertia matrix as the result of the large rotations and the use of orientation parameters such as Euler angles and Euler parameters. This is the case even when rigid body assumptions are used to model track chains. Therefore, using these algorithms to model the more general case of flexible-link kinematic chains can be computationally very inefficient. The joints and inertia nonlinearities coupled with the high frequency contact forces that characterize tracked vehicle systems makes the development of a flexible-link chain model that takes into account the coupling between the rigid body motion and the elastic deformation very difficult or nearly impossible. The proposed new software technology will make the development of these new models feasible by employing ANCF finite elements that lead to a constant mass matrix and to zero Coriolis and centrifugal forces. In fact, an identity generalized mass matrix can be obtained using Cholesky coordinates (Shabana, 1998). This additional unique ANCF feature can be exploited to obtain an optimum sparse matrix structure of the constrained dynamic equations of motion. ANCF finite elements can also be used to develop linear joint connectivity conditions that can be used to eliminate dependent variables at a preprocessing stage allowing for the formulation of the dynamic equations using minimum sets of coordinates and algebraic constraint equations. This new procedure for formulating the dynamic equations allows for developing new FE meshes that have constant inertia and linear connectivity conditions without imposing any restrictions on the amount of rotation or deformation. These linear FE

meshes can be used to significantly reduce the number of Lagrange multipliers associated with the constraint equations as well as the dimension of the augmented form of the matrix equations of motion since ANCF redundant coordinates are eliminated at a preprocessing stage. The new ANCF joint formulation also allows capturing deformation modes at the joint definition points. Furthermore, different joint formulations that define different strain fields can be developed using a continuum mechanics approach that captures joint deformation modes that cannot be captured using rigid body or FFR formulations.

2.4 New Numerical Solution Procedure

Explicit and implicit numerical integration methods are widely used in the solution of the nonlinear equations of motion that govern the dynamics of physics and engineering systems. Nonetheless, many of these methods, when used in solving the MBS differential and algebraic equations, do not ensure that the kinematic constraint equations are satisfied at the position, velocity, and acceleration levels. This can lead to several fundamental and numerical problems and to violation of the basic principles of mechanics. Furthermore, most implicit numerical integration MBS algorithms require the numerical differentiation of the forces; a process that is prone to numerical errors. New MBS software technology must be developed based on sound implementation of the principle of mechanics and based on algorithms that ensure that the numerical solution obtained satisfies these basic principles. It will also be desirable to have an implicit procedure that avoids the numerical differentiation of the forces. Having both explicit and implicit integration methods implemented in the new software will provide the user with the option of selecting the method most suited for his/her application. In this DoD initiative, the implementation of implicit integration methods in a general MBS algorithm that ensures that the kinematic constraint equations are satisfied at all levels will be explored. The new implicit integration methods will take advantage of the sparse matrix structure of the dynamic equations of motion. An implicit sparse matrix integration procedure, called TLSMNI (**T**wo-**L**oop **S**parse **M**atrix **N**umerical **I**ntegration), (Shabana and Hussein, 2009) that ensures that the kinematic constraint equations are satisfied at all levels, exploits the sparse matrix structure of the constrained dynamic equations, and avoids the numerical differentiation of the forces was recently proposed.

The new MBS simulation technology will be based on new concepts and algorithm structure that are fundamentally different from those used in the development of existing MBS commercial codes. New large displacement FE meshes consistent with CAD geometry and suited for integration with computational MBS algorithms will be used as the foundation for a new computational environment that allows for the virtual prototyping of new detailed wheeled and tracked vehicle/terrain models. The new computational framework must be general in order to allow for the analysis, design, and performance evaluation of general MBS systems that consist of rigid, flexible, and very flexible bodies. In the following sections, the approaches that will be used in developing the new MBS software technology are discussed.

3. GENERAL APPROACHES

This section and the following sections describe the general approaches that can be used for developing new MBS simulation technology for the virtual prototyping of detailed vehicle models. The approaches will be general in order to ensure that the new software environment will also allow for modeling general MBS applications that include equipment, machines, aerospace systems, and bio-mechanics and biological systems. This is in fact one of the basic requirements for general MBS algorithms that solve the differential and algebraic equations of physics and engineering systems that consist of interconnected rigid and deformable bodies. The new computational environment must be designed to maintain some of the desirable modeling capabilities and features offered by existing MBS simulation codes. This can be achieved by developing a new computational framework that allows for integrating different formulations

and solution procedures. Such a computational framework will have an algorithm structure that is fundamentally different from existing MBS algorithm structures in order to accomplish the following:

1) Develop an efficient and simple interface between CAD systems and MBS simulation codes. Such an interface will be used to avoid the model geometric distortions. The integration of computational CG/FE/MBS algorithms is necessary in order to have accurate models of system components with complex geometry.
2) Allow for the implementation of general material models and deformation description. Existing MBS algorithms cannot be used systematically for the FE analysis of large deformation and are not designed for the implementation of general material laws that are required in modeling many MBS applications. The new software must remedy this deficiency.
3) Develop new FE meshes that have constant inertia and linear joint connectivity conditions. The new algorithms must be based on new analysis concepts that lead to new FE meshes that have constant inertia matrix, and zero Coriolis and centrifugal forces. This feature will allow for obtaining an optimum sparse matrix structure of the dynamic equations of motion. The new FE meshes will also allow for formulating chain joints using linear connectivity conditions, thereby eliminating dependent variables at a preprocessing stage. The new FE meshes will also allow for the use of compliant joints that can be defined using bushing elements or continuum based ANCF models.
4) Allow for the implementation of new numerical integration procedures. Most implicit integration methods implemented in MBS codes require numerical differentiation of the forces and do not ensure that the kinematic constraint equations are satisfied at the position, velocity, and acceleration levels. Furthermore, many of these implicit methods do not exploit the sparse matrix structure of the MBS dynamic equations. In the new MBS software technology, new implicit numerical integration procedures that do not require the numerical differentiation of the forces, ensure that the constraint equations are satisfied at all levels, and exploit the sparse matrix structure of the MBS dynamic equations (Shabana and Hussein, 2009).

In the following sections, more detailed discussion of the specific approaches that will be used in developing the new MBS software technology will be presented.

4. INTEGRATION OF CG AND MBS ALGORITHMS

In order to develop a general and efficient MBS computer algorithm for solving rigid body, small deformation, and large deformation problems; different kinematic descriptions must be used. Three different types of coordinates will be used to describe the motion of the interconnected bodies. The first set of coordinates is the *reference coordinates* $\mathbf{q}_r$ that describe the motion of rigid bodies or frames of reference. The use of these coordinates is necessary to avoid using a very high modulus of elasticity to model rigid bodies. The second set of coordinates is the set of *elastic coordinates* $\mathbf{q}_f$ that describe the small deformations with respect to the body references. Because of the definition of these elastic coordinates, a local linear problem can be defined to systematically eliminate insignificant high frequency modes. The vectors $\mathbf{q}_r$ and $\mathbf{q}_f$ are used to develop the FFR formulation currently implemented in most commercial MBS computer programs (Roberson and Schwertassek, 1988; Schiehlen, 1997; Shabana, 2005). The FE/FFR formulation remains an effective method for modeling small deformations. The new software technology must also provide some of the important capabilities and features offered by existing commercial MBS software; including an FFR implementation.

As previously mentioned, existing commercial MBS computer programs are not designed for the systematic FE solution of large deformation problems. It is the goal of the DoD initiative to develop new MBS software technology that will allow for solving these problems by using a third set of coordinates,

the ANCF *absolute nodal coordinates* $\mathbf{q}_a$, to develop new MBS models that cannot be examined using existing software technology. In the ANCF description, the assumed displacement field of an element j can be written as $\mathbf{r}^j\left(\mathbf{x}^j,t\right)=\mathbf{S}^j\left(\mathbf{x}^j\right)\mathbf{e}^j\left(t\right)$, where $\mathbf{r}^j$ is the global position vector of an arbitrary point on the finite element, $\mathbf{x}^j=\left[x \quad y \quad z\right]^T$ is the vector of the spatial coordinates of the finite element, $\mathbf{S}^j$ is the element shape function matrix, $\mathbf{e}^j$ is the element vector of nodal coordinates, and t is time. The ANCF kinematic description differs from the conventional finite element description since infinitesimal or finite rotations are not used as nodal coordinates; instead, global position vectors and position vector gradients are used as nodal coordinates. The ANCF description correctly describes rigid body motion, leads to zero strains under an arbitrary rigid body rotation, and allows for modeling complex geometry including discontinuities and T-sections which cannot be modeled using conventional B-spline and NURBS representations used in CAD systems (Piegl and Tiller, 1997; Cottrell et al., 2007). Furthermore, B-spline and NURBS representation can be converted without any geometric distortion to an ANCF mesh, thereby preserving the geometry (Sanborn and Shabana, 2009; Lan and Shabana, 2010). This important feature distinguishes ANCF finite elements from other conventional structural finite elements (beams, plates, and shells) which do not correctly describe arbitrary rigid body displacements and do not preserve CAD geometry when converted to FE mesh.

The feasibility of successful integration of CG/FE/MBS algorithms can be demonstrated using the ANCF description which is consistent with the description used in CAD systems. This integration is necessary, as previously mentioned, in order to preserve the geometry created in CAD systems and have an analysis model that is consistent with the CAD model. Existing MBS commercial codes do not preserve CAD geometry because of the nature of the finite elements used, as previously discussed. The successful integration of CG/FE/MBS algorithms will lead to a new computational framework that will allow for more accurate and efficient modeling of complex physics and engineering systems. The goals of the DoD initiative can be realized by addressing several fundamental issues that include relationship between the CG knot multiplicity and MBS constraint equations, the order of interpolations in the geometry and kinematic description, the generality of the ANCF representation as compared to CG description, the limitations of CG methods as analysis tool (isogeometric approach), and the description of the discontinuities that characterize MBS and structural system applications.

5. LARGE DEFORMATION AND MATERIAL NONLINEARITIES

Modeling vehicle, machine, aerospace, biomechanics, and biological system components such as tires, belt drives, rubber chains, soil, cables, ligaments, soft tissues, muscles, parachutes, etc. requires the use of general constitutive material models that cannot be implemented in existing MBS computer codes that are based on conventional finite elements. Conventional structural finite elements used by these codes are based on classical beam, plate, and shell theories that employ simplifying assumptions making it difficult to adopt a general continuum mechanics approach and general constitutive models. The FE floating frame of reference (FFR) formulation implemented in most existing flexible MBS commercial computer codes was developed approximately three decades ago. Since this development, no new major motion modeling formulations have been implemented in most widely used commercial MBS computer programs. As previously mentioned, the FFR formulation is based on a procedure that employs linear modes for the description of the body deformations. This procedure, therefore, is not suited for the analysis of large deformation or the implementation of general material models. Furthermore, the FFR formulation leads to a highly nonlinear inertia matrix, non-zero Coriolis and centrifugal forces, and to highly nonlinear kinematic constraint equations because of the nature of the coordinates used in this formulation. Such a formulation can also be very inefficient in developing flexible-link chain models, as previously discussed.

Because large deformation problems cannot be systematically solved using the FE/FFR formulation implemented in most commercial MBS codes, there is a need to use new FE formulations that allow for general motion description and for the implementation of general constitutive laws such as Neo-Hookean,

Mooney-Rivlin, and soil models. ANCF finite elements, as previously mentioned, do not suffer from the serious limitations of other conventional structural elements and have a kinematic description that is consistent with the general theory of continuum mechanics. Using ANCF finite elements, the *matrix of position vector gradients* $\mathbf{J}$ can be obtained and used to evaluate the *Green-Lagrange strain tensor* $\boldsymbol{\varepsilon} = \left(\mathbf{J}^T\mathbf{J} - \mathbf{I}\right)/2$ that defines the strain components in their most general form. The matrix of position vector gradients $\mathbf{J}$ can also be used to evaluate the *right Cauchy-Green strain tensor* $\mathbf{C}_r = \mathbf{J}^T\mathbf{J}$, the invariants of this tensor, I_1, I_2, and I_3, enter into the formulation of many nonlinear constitutive models. For example in the case of the Neo-Hookean materials, the strain energy U can be written in terms of the invariants of the tensor $\mathbf{C}_r$ as

$$U = \left(\mu\left(I_1 - 3\right) - \mu \ln J + \lambda\left(\ln J\right)^2\right)/2 \tag{1}$$

where μ and λ are Lame's constants used in the linear theory, and J is the determinant of the matrix of position vector gradients $\mathbf{J}$. Using the expression for the strain energy, the stress-strain relationship (constitutive equations) can be developed. ANCF finite elements also allow for the use of other general material models including Mooney-Rivlin constitutive law which is suited for modeling rubber material used in tires, belt drives, cables, and rubber chains. These ANCF elements can also be used in modeling bio-materials as well as plastic material behavior as in the case of soils. This unique and important feature of ANCF structural elements (beams, plates, and shells) allows for developing accurate FE models for MBS components such as tires, belts, rubber chains, cables, soils, parachutes, ligaments, muscles, soft tissues, etc.

Another important issue related to the generality of the dynamic models is the displacement modes captured by the MBS solution algorithms. The general displacement of material elements can be described in terms of 12 independent variables; three translations, three rigid body rotations, and six deformation modes (normal and shear strains). Not all these displacement modes are captured by existing FE/MBS modeling algorithms. For example in the classical beam theories, the dimensions of the cross section are assumed to remain constant regardless of the load applied; elongation or shortening of the beam does not lead to a change in the dimension of the cross section. A track link in a tracked vehicle subjected to excessive compressive load is assumed to have constant cross section and constant thickness regardless of the temperature and the magnitude of the load. These unrealistic assumptions do not allow for the use of existing MBS commercial codes in many important applications in which these unrealistic assumptions must be relaxed. For this reason, it is necessary when developing new MBS software technology to use a new ANCF solution algorithm that relaxes these assumptions and captures the coupling between different modes of deformation. ANCF finite elements, for example, can capture the change in the cross section area as defined by Nanson's formula

$$ds = \left(J/\sqrt{\mathbf{n}^T\mathbf{J}\mathbf{J}^T\mathbf{n}}\right)dS \tag{2}$$

where s and S are the areas in the current and reference configurations, respectively, $\mathbf{J}$ is the matrix of position vector gradients, J is the determinant of $\mathbf{J}$, and $\mathbf{n}$ is a unit vector normal to the cross section (Ogden, 1984; Shabana, 2012). A MBS/ANCF approach can therefore be used to develop a more general MBS algorithm that allows for systematically modeling large deformations and for a straight forward implementation of general constitutive equations. Such a new algorithm can be used as the basis for the development of a new software technology that can be integrated with CAD systems, as previously explained.

6. NEW FE/MBS MESHES

Large scale tracked vehicle models consist of a large number of bodies connected by joints or bushings that allow for large relative rotations. The links of the track chains can be modeled as rigid or flexible bodies. Rigid link chain models do not capture the effect of the deformations due to excessive forces and thermal loads. While rubber chain (belt) models have been recently developed at the University of Illinois at Chicago (UIC), no models of flexible-link chains of tracked vehicles have been yet developed. Developing these models using existing MBS software technology can be very inefficient or even impossible because of the complexity of such models. MBS algorithms used in existing commercial codes lead to highly nonlinear joint formulations and highly nonlinear inertia matrix as the result of the large rotations and the use of orientation parameters such as Euler angles and Euler parameters. This is in addition to the high frequency contact forces that can make modeling tracked vehicles a challenging task even when rigid body assumptions are used. Using flexible MBS/FFR algorithms implemented in commercial codes to model flexible-link kinematic chains will also be computationally inefficient. The joints and inertia nonlinearities coupled with the high frequency deformation modes and contact forces that characterize tracked vehicle system applications make the development of a flexible-link chain model that takes into account the coupling between the rigid body motion and the elastic deformation using existing MBS software technology nearly impossible.

The proposed new software technology must make feasible the development of new detailed flexible-link chain tracked vehicle models as well as other physics and engineering models that include details that cannot be captured by existing MBS software technology. This can be achieved by developing new FE/MBS meshes that are based on new concepts. For instance, a three-dimensional chain model developed in a general purpose FE or MBS code will have a highly nonlinear inertia matrix and nonlinear connectivity conditions because of the nature of generalized coordinates used in FE and MBS formulations, as previously explained. ANCF finite elements, on the other hand, lead to a constant mass matrix and to zero Coriolis and centrifugal forces. It can be shown that the use of the ANCF displacement field $\mathbf{r}^j\left(\mathbf{x}^j,t\right)=\mathbf{S}^j\left(\mathbf{x}^j\right)\mathbf{e}^j\left(t\right)$ will always lead to the constant element mass matrix $\mathbf{M}^j=\int_{V^j}\rho^j\mathbf{S}^{jT}\mathbf{S}^j dV^j$, where ρ^j and V^j are, respectively, the mass density and volume of the element. This important ANCF result is valid regardless of the amount of rotation or deformation within the finite element. Because of this ANCF property, an identity generalized mass matrix can be obtained using *Cholesky coordinates* (Shabana, 1998). This unique ANCF feature can be exploited to obtain an optimum sparse matrix structure of the constrained dynamic equations of motion.

ANCF finite elements can also be used to develop linear joint connectivity conditions that can be used to eliminate dependent variables at a preprocessing stage allowing for the formulation of the dynamic equations using minimum set of coordinates and algebraic constraint equations. While, for example, the formulation of revolute joints is highly nonlinear in the case of rigid body mechanics, linear revolute joint formulations can be developed using ANCF finite elements. The formulation of the revolute joint between two ANCF elements i and j employs the following six scalar equations defined at the joint node:

$$\mathbf{r}^i=\mathbf{r}^j,\qquad \mathbf{r}_\alpha^i=\mathbf{r}_\alpha^j \tag{3}$$

where α is the coordinate line that defines the joint axis; α can be x, y, or z or any other coordinate line, and $\mathbf{r}_\alpha=\partial\mathbf{r}/\partial\alpha$. The six scalar constraint equations eliminate six degrees of freedom; three translations, two rotations, and one deformation mode. This joint model ensures C^1 continuity with respect to the coordinate line α and C^0 continuity with respect to the other two parameters. That is, the Lagrangian strain component $\varepsilon_{\alpha\alpha}=\left(\mathbf{r}_\alpha^T\mathbf{r}_\alpha-1\right)/2$ is continuous at the joint definition point, while the other

five strain components can be discontinuous. Such ANCF constraint equations are linear in the nodal coordinates, and therefore, the dependent variables can be eliminated at a preprocessing stage.

The fact that the new procedure for formulating the dynamic equations allows for developing new FE meshes that have constant inertia and linear connectivity conditions without imposing any restriction on the amount of rotation or deformation within the ANCF finite elements is crucial in the development of an efficient and general MBS algorithms. The new linear FE meshes can be used to obtain an optimum sparse matrix structure, to significantly reduce the number of Lagrange multipliers associated with the constraint equations, and to significantly reduce the dimension of the augmented form of the matrix equation of motion since ANCF redundant coordinates are eliminated at a preprocessing stage. Furthermore, the new ANCF joint formulation allows capturing deformation modes at the joint definition points and also allows for imposing different degrees of continuity for different coordinate lines (parameters). Different joint formulations that define different strain fields can be developed using a continuum mechanics approach that captures joint deformation modes that cannot be captured using rigid body or FFR formulations.

7. NUMERICAL INTEGRATION METHODS

General purpose MBS computer codes must provide the options of implicit and explicit numerical integrations. The choice of the integration method depends on the application under investigation. The implementation of implicit integration methods in existing commercial MBS codes needs to be carefully examined for the following reasons:

1) Most implicit numerical integration implementations require numerical differentiation of the applied forces. In many MBS applications, the forces are not defined analytically, but they are given using spline function representations. Numerical differentiation of the forces is prone to error and can lead to serious numerical problems, particularly in the case of flexible bodies.
2) Many MBS implicit numerical integration procedures do not ensure that the kinematic constraint equations are satisfied at all levels (position, velocity, and acceleration). This is an important issue since violation of the constraint equations at any level can lead to violation of the principles of mechanics, including the principle of work and energy.
3) Many MBS implicit numerical integration methods do not exploit the sparse matrix structure of the MBS dynamic equations because of the nature of the iterative procedure used to solve for the resulting nonlinear algebraic equations. In many of these methods, A Newton-Raphson algorithm is used in the solution procedure. The coefficient matrix that appears in the equations used to solve for the Newton-differences is not a sparse matrix.

An implicit integration procedure (TLSMNI) that addresses these issues was recently proposed (Shabana and Hussein, 2009). The proposed TLSMNI procedure has a potential for solving the above mentioned problems since it does not require the numerical differentiation of the forces; it ensures that the constraint equations are satisfied at the position, velocity, and acceleration levels; and it exploits the sparse matrix structure of the resulting MBS equations at every step of the solution procedure. The use of such a procedure will not lead to a violation of the mechanics principles, will not cause energy drift, will be more efficient since sparsity is exploited, and will not lead to significant numerical errors because numerical differentiation is avoided.

In addition to the implementation of the implicit integration procedures, the proposed new software must also provide the option of using explicit integration methods which do not filter out high frequency modes and capture more details that can be significant in some MBS applications. Both the explicit and implicit numerical integration implementations will allow for solving the differential and algebraic equations that govern the motion of MBS applications, and both approaches will ensure that the constraint equations are not violated at any level.

It is important to point out that some fully parameterized ANCF finite elements can suffer from locking problems when used in modeling thin and stiff structures. Efficient methods for formulating the elastic forces need to be developed in order to avoid these locking problems. Also in some applications, the use of the FE method can lead to large system of equations as pointed out by Melanz et el. (2012) who proposed a method to alleviate this problem using three tools: (1) an implicit time-stepping algorithm, (2) fine-grained parallel processing on the Graphics Processing Unit (GPU), and (3) enabling parallelism through a novel Constraint-Based Mesh (CBM) approach. They demonstrated that the combination of these tools results in a fast solution process that scales linearly for large numbers of elements, allowing meaningful engineering problems to be solved.

8. SUMMARY

This paper discusses a new DoD initiative for the development of a new generation of MBS software technology that will allow for the integration of computer aided design and analysis (I-CAD-A). The new computational environment will be used in the simulation of models that include details that cannot be captured by existing MBS software.

Acknowledgements

The research presented in this paper was supported by the DoD SBIR grant number W56HZV-13-C-0032 sponsored by the US Army Tank Automotive Research, Development, and Engineering Center (TARDEC).

Disclaimer

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